Hot Electron Effects in the 2D Superconductor-Insulator Transition

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Abstract

The parallel magnetic field tuned two-dimensional superconductor-insulator transition has been investigated in ultrathin films of amorphous Bi. The resistance is found to be independent of temperature on both sides of the transition below approximately 120 mK. Several observations suggest that this regime is not intrinsically "metallic" but results from the failure of the films' electrons to cool. The onset of this temperature-independent regime can be moved to higher temperatures by either increasing the measuring current or the level of electromagnetic noise. Temperature scaling is successful above 120 mK. Electric field scaling can be mapped onto temperature scaling by relating the electric fields to elevated electron temperatures. These results cast doubt on the existence of an intrinsic metallic regime and on the independent determination of the correlation length and dynamical critical exponents obtained by combining the results of electric field and temperature scaling.

Quantum phase transitions (QPTs) [1] have received a lot of attention as quantum criticality is a ubiquitous feature of many strongly correlated electron systems. In a QPT, a system flows towards one of two different ground states as $T \rightarrow 0$, depending on the value of a "tuning" parameter in its Hamiltonian. The nature of the transition is determined by the correlation length and dynamical critical exponents, ν and z respectively. Non-linear conductivity [1, 2, 3, 4] near the quantum critical point is important because the results of the finite size scaling under changes of electric field can be combined with the scaling under changes of temperature to determine the values of ν and z. In this process, an important issue is the extent to which intrinsic non-linear response is more important than Joule heating. While there is a material dependent criterion [1], it is based on dimensional analysis and may thus lack important multiplicative factors.

A second issue is the existence of metallic phases at low temperatures near the quantum critical point. The Bose-Hubbard model of the superconductor-insulator (SI) transition in two dimensions predicts a metallic ground state having finite resistance at zero temperature only at the critical value of the tuning parameter [5]; slight deviations from criticality result in either superconducting or insulating ground states. However, as measurements have been extended to lower temperatures, temperature-independent resistances have been found on both sides of the transition over an extended range of tuning parameters [6, 7, 8, 9]. There have been a couple of claims that these are evidence of an intrinsic metallic regime between the superconducting and insulating states [7, 9], which have led to considerable discussion of reformulations of the SI transition scenario [10, 11, 12, 13]. The nature of this resistance saturation is far from certain because of difficulties with electrical measurements on ultrathin films at mK temperatures. The electronic heat capacities of such films are very small, so that even modest levels of dissipation may prevent cooling of the films' electrons. Dissipation can be due to either the measuring current or from currents that result from the electromagnetic noise environment. At low temperatures, the dominant cooling mechanism for electrons is through the electron-phonon interaction, and this coupling is weak at mK temperatures [14]. A refrigerator could thus cool a film's phonons more effectively than its electrons, resulting in a temperature-independent resistance since the film would be measured at its minimum achievable electron temperature over an extended range of lower phonon or lattice temperatures.

We discuss here the role of electron heating in the 2D SI transition in ultrathin films. An electric field scaling analysis that successfully collapses data is shown to be a direct consequence of heating and not due to quantum critical non-linear electrical response. Since electric field scaling can be mapped onto temperature scaling by relating electric fields to elevated temperatures, the separate determination of ν and z is an open issue. Also, the temperature-independent resistance below 120 mK that has previously been asserted for other superconducting films to be evidence of a novel metallic state is likely a consequence of heating due to the electromagnetic environment. This regime of temperature-independent resistance prevents the extension of temperature scaling below 120 mK. The relevance of these observations to other 2D SI transitions is discussed.

A 10.4 Å thick a-Bi film was deposited onto 10 Å of amorphous antimony (a-Sb) that was pre-deposited onto a $SrTiO_3$ substrate that was held at 6 K during depositions. Such films are believed to be disordered on an atomic, rather than mesoscopic, length scale; recent structural studies support this hypothesis [15]. The film was then transferred to a dilution refrigerator without removing the sample from vacuum or warming it above 15 K [16]. The system was heavily shielded and electrically filtered to minimize the electromagnetic noise in the film's environment [18] with AC filters at 300 K to remove noise at 60 Hz and at radio frequencies and at mK temperatures to remove noise at GHz frequencies. The sheet resistance, R, and the differential sheet resistance, $R_D = dV/dI$, were measured by applying a DC current,

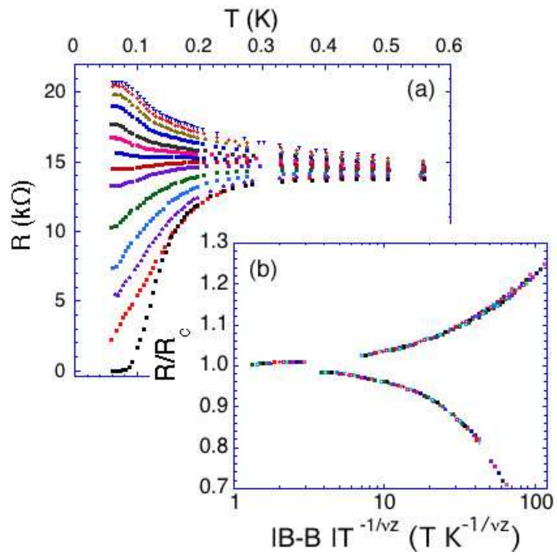

FIG. 1: (a) Resistance vs. temperature at $B = 0$ (bottom), 2, 3, 4, 5, 6, 6.5, 7, 7.5, 8, 9, 10, 11, and 12 T (top). (b) Temperature scaling for this transition.

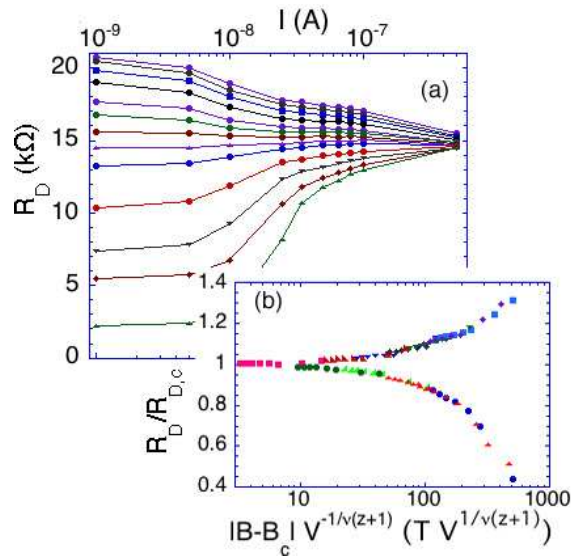

FIG. 2: (a) Differential resistance vs. current at 65 mK for $B = 2$ (bottom), 3, 4, 5, 6, 6.5, 7, 7.5, 8, 9, 10, 11, and 12 T (top). (b) Electric field scaling for this transition.

I, across the film and measuring voltage, V, across an area of $(0.5mm)^2$ of film. Resistance was determined from $(V(I) - V(-I))/(2I)$, with $I = 1\ nA$. R_D was determined from $V((I+\Delta I)-V(I-\Delta I))/2\Delta I$ with $\Delta I = 1$ nA, with $I = 0$, 5, 10, 25, 35, 50, 65, 80, 100, and 500 nA.

Magnetic fields, B, applied parallel to the film plane and perpendicular to the direction of the measuring current, were used to tune the transition. In Fig. 1(a), $R(T)$ is shown for several values of B. At $B = 0$ T, T_c was about 80 mK. At 12 T, $R(T)$ was best described by 2D Mott variable range hopping from 120 mK to 10 K. The $R(T, B)$ data were then analyzed using temperature scaling. Note that data at temperatures below 120 mK were excluded from the analysis as below 120 mK $R(T)$ deviated from its high temperature behavior and became independent of temperature. For isotherms between 120 and 250 mK, for B between 3 and 12 T, values of $R(B)$ crossed at a critical resistance R_c = 15,200 Ω and a critical field $B_c = 6.87$ T. In Fig. 1(b), R/R_c is plotted against the temperature scaling parameter $|B - B_c|T^{-1/\nu z}$ with the value of $\nu z = 0.68 \pm 0.05$ that produced the best collapse of data. This value of νz agrees with those found when perpendicular fields [17], electrostatic charge transfer [18], and parallel fields [18] were used as tuning parameters for a-Bi films.

Data were collected for electric field scaling by recording R_D at 10 values of bias current at the same B fields and temperatures as for the temperature scaling. In Fig. 2(a), we show R_D vs. I recorded at 65 mK. For this data, curves of R_D vs. B at different values of I crossed at the same values of $R_{D,c}$ and B_c as in temperature scaling, within uncertainty. We show the electric field scaling analysis in Fig. 2(b), where $R_D/R_{D,c}$ is plotted against the electric field scaling function $|B - B_c|V^{-1/\nu(z+1)}$ for the value of $\nu(z + 1) = 2.0 \pm 0.1$ that produced the best collapse of data. The two scaling analyses suggest that $\nu z \sim 0.68$ and $\nu(z + 1) \sim 2.0$, which then yield $\nu \sim 1.3$ and $z \sim 0.5$. However, this value of z is unphysical as z is believed to be either 1 or 2 for charged Bose systems, depending on their interactions [19].

We now show that the currents in the electric field scaling analysis heat the electrons. Each value of current corresponds to an elevated electron temperature. When this is taken into account, the collapse in electric field scaling can be shown to be due to temperature scaling.

Some evidence for heating by the measuring current is seen in the temperature dependence of R_D. In Figs. 3(a)-3(d), we show curves of $R_D(T)$ for magnetic fields between 0 and 12 T at four illustrative bias currents, 0, 25, 65, and 100 nA. Above 300 mK, $R_D(T)$ curves were independent of I for given value of B. However, below 300 mK, R_D was independent of temperature at high I. Indeed, with $I = 100$ nA, R_D was independent of temperature up to almost 200 mK, which is highly suggestive that this current heated the electrons as high as 200 mK for all refrigerator temperatures below 200 mK.

We now explore the consequences of the hypothesis that electron heating is the cause of deviations of R_D from R at given B and T. We use $R(T)$ as a thermometer, so that each value of resistance corresponds to an electron temperature. Keeping the refrigerator at 65 mK, each current produces a value of R_D that corresponds

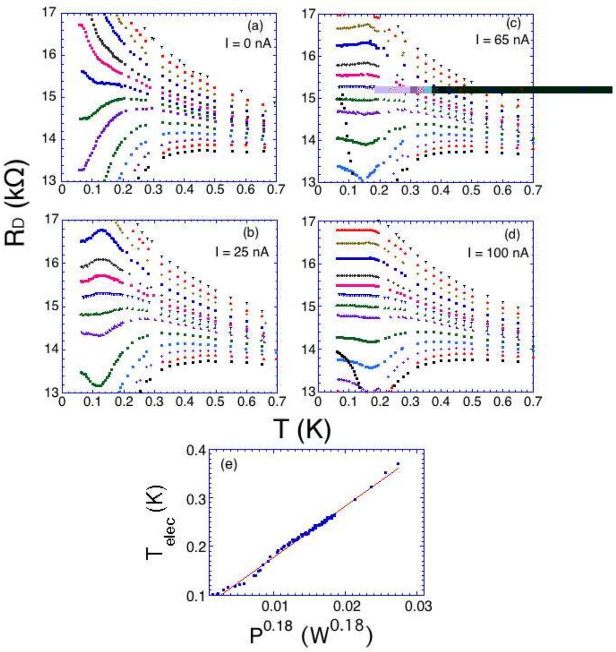

FIG. 3: Differential resistance vs. temperature at 0 (bottom), 2, 3, 4, 5, 6, 6.5, 7,7.5, 8, 9, 10, 11, and 12 T (top), for four measurement currents. (e) T_{elec} vs. measurement power.

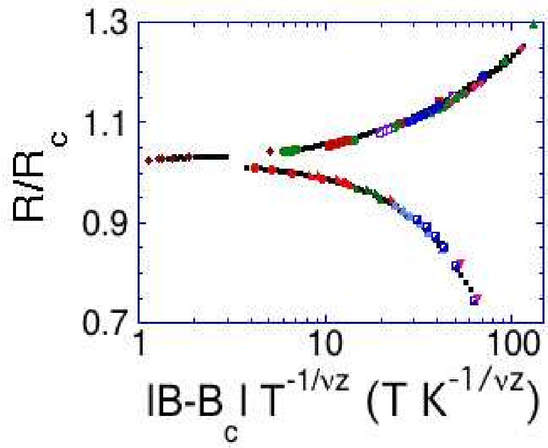

FIG. 4: Temperature scaling for data obtained by raising refrigerator temperature (small black circles) and for data obtained by heating the electrons with elevated measurement currents (larger color symbols).

to a higher effective electron temperature, T_{elec}. Thus, we assume that the only effect of increased current is to heat the film's electrons. The effective electron temperature is found to increase with power as $T_{elec} \sim P^{0.18}$ for $I \geq 5$ nA which is shown in Fig. 3(e) for a 7.89 $\mathring{A}$ thick film of a similar sample, where more data were available from more extensive measurements of $I - V$ characteristics. This same exponent was found, within ± 0.05, for the 10.4 $\mathring{A}$ thick film, where less data were available. This power dependence is very close to that proposed by Wellstood *et al.* [14] ($T_{min} \sim P^{1/5}$) to describe the relationship between a metal film's minimum electron temperature and measurement power. They verified this relationship experimentally by varying the bias power in AuCu films and determining the electron temperature using noise thermometry.

We can now map electric field scaling onto temperature scaling. On the superconducting side of the transition, $I - V$ characteristics are Josephson-like, while on the insulating side, they are single-particle like. Near B_c, they are only slightly non-linear. Over the current range used for electric field scaling ($I \geq 5nA$), $V \sim I^{1.05}$ at 3 T, while $V \sim I^{0.95}$ at 12 T. The average effect is roughly $I \sim V$. Since $P = IV$, then $T_{elec} \sim V^{0.36}$, or $V \sim T_{elec}^{2.78}$. If this relationship for V, which is proportional to the electric field, is inserted into the electric field scaling relation, we find $R_D/R_{D,c} = F(|B - B_c|T_{elec}^{-1/0.72})$. This value of $\nu z = 0.72$ agrees within error with that found by temperature scaling. This suggests that the electric field scaling works because it is effectively temperature scaling, and increased measuring current increases temperature. There is a slight uncertainty in this result since I vs. V is slightly different for each value of B. However, when data used for electric field scaling are analyzed using temperature scaling by determining the electron temperature using $R(T)$ as a thermometer, the resulting analysis collapses on top of the temperature scaling analysis from Fig. 2. The exponent product and scaling function are *identical* for electrons warmed by these two methods. This is shown in Fig. 4.

Thus, for *a*-Bi films, electric field scaling cannot provide information to separately determine ν and z. Is this merely a property of the *a*-Bi/*a*-Sb film, or is it a more general result? In the limit of zero temperature, non-linear transport effects are expected to compete with Joule heating, with material specific properties being important. The electron temperature varies with power as $T_{elec} \sim P^{1/\theta}$ with $\theta = p + 2$, where p is the temperature coefficient of the inelastic electron-phonon scattering rate, $\tau_{in}^{-1} \sim T^p$ [24]. There is a criterion [1] that for $\frac{2}{\theta} < \frac{z}{z+1}$ Joule heating, rather than intrinsic non-linear effects will dominate. This criteria arises from a dimensional analysis argument that may ignore important multiplicative factors. We do not know z, but assuming it to be 1 or 2, the value of θ in *a*-Bi meets this criterion as stated. However, even in the earlier work of Yazdani and Kapitulnik on MoGe thin films [6], in which scaling analyses revealed apparent values of $\nu z \sim 1.35$ and $\nu(z + 1) \sim 2.65$, which yielded $\nu \sim 1.3$ and $z \sim 1$, heating may actually be responsible. It is known that $p = 2$ in MoGe [20], so that $\theta = 4$. This puts MoGe in the "marginally dangerous" category in which

both heating and intrinsic effects may be important [1]. Indeed, this value of θ implies that $V \sim T^2$, implying that in the electric field scaling of Yazdani and Kapitulnik, $V^{-1/2.65} \sim T_{elec}^{-2/2.65} = T_{elec}^{-1/1.375}$. Thus, electric field scaling maps well onto temperature scaling if one assumes heating is responsible for the electric field dependence.

We note similarities of our results with those of Golubkov *et al.* [21] in In_2O_3. They suggested that electron heating was dominant on the insulating side of the perpendicular field tuned transition with $\theta = 5$. However, they found that data collapse in an electric field scaling analysis was "unsuccessful." This may imply that vortex motion is a more dominant effect than heating on the superconducting side of their transition.

Indeed, most dirty samples have values of p between 2 and 4 [22] raising the possibility that heating will dominate intrinsic non-linear effects in most materials.

Given that elevated current can cause Joule heating in these films, what happens in measurements made with minimal bias currents? A second cause of heating is the current induced in a film by its electromagnetic environment. In a similar series of films, we measured $R(T)$ before and after removal of an AC filter that removed noise at 60 Hz. $R(T)$ was unchanged above 150 mK. The temperature below which R became independent of temperature moved to higher T after the removal of the filter. Since the DC resistance cannot change in any way by the removal of an AC filter, this must be caused by heating of electrons in the film due to increased noise current. It is reasonable to assume that even with very strong filtering, the residual electromagnetic noise caused $R(T)$ to become independent of temperature as $T \to 0$ as the electron-phonon coupling weakens.

One might ask how general is the above conclusion. The extent of the shielding and filtering in the measurements on nominally homogeneous MoGe and Ta films used as the basis for claims of a low T metallic regime is not revealed in Refs. 7 and 9. Measurements of mesoscopically clustered films show minima in $R(T)$ in $B = 0$ at the bulk transition temperature, while the resistance is independent of temperature at temperatures below these minima [23]. It is possible that these films exhibit intrinsic metallic phases at low temperatures, as the temperature independence extends to temperatures on the order of several K, in a regime where electron-phonon coupling and other heat transfer mechanisms should be strong. On the other hand, it is possible that these films act as better antennae for radiation or that the clusters change the mechanism of heat transfer in an unknown manner. A final caveat is that although resistance saturation for parallel-field, perpendicular field, electrostatic, and thickness tuned transitions are qualitatively similar, the perpendicular field case involves vortices and the physics may be different.

In conclusion, we have found that measuring currents in ultrathin a-Bi/a-Sb films can heat electrons out of equilibrium with their environment. This prevents electric field scaling from yielding information to separately determine ν and z. Residual electromagnetic noise and non-zero measuring currents may lead to the so-called metallic regime observed in a number of experiments at temperatures below about 150 mK.

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